GOATS'2002
Multi-static Active Acoustics in Shallow Water

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LONG-TERM GOAL

Develop environmentally adaptive bi- and multi-static sonar concepts for autonomous underwater vehicle networks for detection and classification of proud and buried targets in very shallow water.

OBJECTIVES

The objective of the ocean acoustics components of the GOATS project is to develop a fundamental understanding of the 3D mid-frequency (1-20 kHz) acoustic environment associated with the mine countermeasures (MCM) problem in shallow water (SW) and very shallow water (VSW) and to develop efficient physics based propagation and scattering models incorporating aspect-dependent targets and seabed features, and the waveguide multipath effects. The goal is a consistent physics-based modeling framework for high-fidelity simulation of bi-and multistatic sonar configurations for VSW MCM which may form the basis for new acoustic classification techniques based on spatial and temporal target resonance characteristics. Specific scientific objectives include the investigation of mechanisms responsible for sub-critical penetration into sediments in the mid-frequency regime (1-20 kHz), the effects of sediment porosity, and the coupling between the structural acoustics of targets and the environmental acoustics of the littoral waveguides.

APPROACH

The development of GOATS (Generic Ocean Array Technology Sonar) is a highly interdisciplinary effort, involving experiments, and theory and model development in advanced acoustics, signal processing, and robotics. The center piece of the research effort has been a series of Joint Research Projects (JRP) with SACLANTCEN. The joint effort was initiated with the the GOATS'98 pilot experiment [2] and continued with the GOATS'2000 and BP02/MASAI02 experiments. Currently the collaboration is being continued under two SACLANTCEN JRPs, one on hybrid target scattering modeling, and one on Focused Acoustic Field (FAF), with a joint experiment being planned for July 2004. In addition to the field experiments involving significant resources provided by SACLANTCEN, GOATS uses modeling and simulation to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of SW and VSW.

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The acoustic modeling effort is centered around the OASES environmental acoustic modeling framework developed at MIT [1,4]. OASES is a widely distributed suite of models covering a variety of ocean waveguide and source/receiver representations. Thus, the most recent developments are computational modules for full wave theory modeling of mono-and bistatic target scattering and reverberation in shallow water waveguides. The most recently developed module, OASES-3D provides wave-theory modeling of the full 3-D acoustic environment associated with mono- and bi-static configurations in SW and VSW with aspect-dependent targets and reverberation features [3,4]. It incorporates environmental acoustic features specifically associated with bi-static sonar concepts in shallow water, including aspect-dependent target models, seabed porosity, and scattering from anisotropic seabed roughness such as sand ripples.

In addition to the acoustic modeling, a significant effort is invested in the development of signal processing algorithms for the multi-static GOATS concept, including bistatic generalizations of synthetic aperture processing, and algorithms for concurrent detection, tracking and classification of seabed targets. This work is described in the companion report for Code 321TS and 321 OE, which is sponsoring this component.

In addition to the acoustic research, GOATS involves a significant effort addressing the fundamental robotics issues associated with the collaborative operation of multiple autonomous underwater vehicles in shallow water, including navigation, inter-platform acoustic communication, and adaptive, cooperative behavior. Specifically the current effort explores the development of Concurrent Mapping and Localization (CML) algorithms for networks of AUVs, and the implementation of efficient inter-vehicle acoustic communication protocols enabling the cooperative behavior which is crucial to the implementation of the GOATS concept. This work, including recent results from the GOATS2002 experiment are described in the companion report for Code 321OE.

WORK COMPLETED

<u>OASES Target Scattering Model</u>

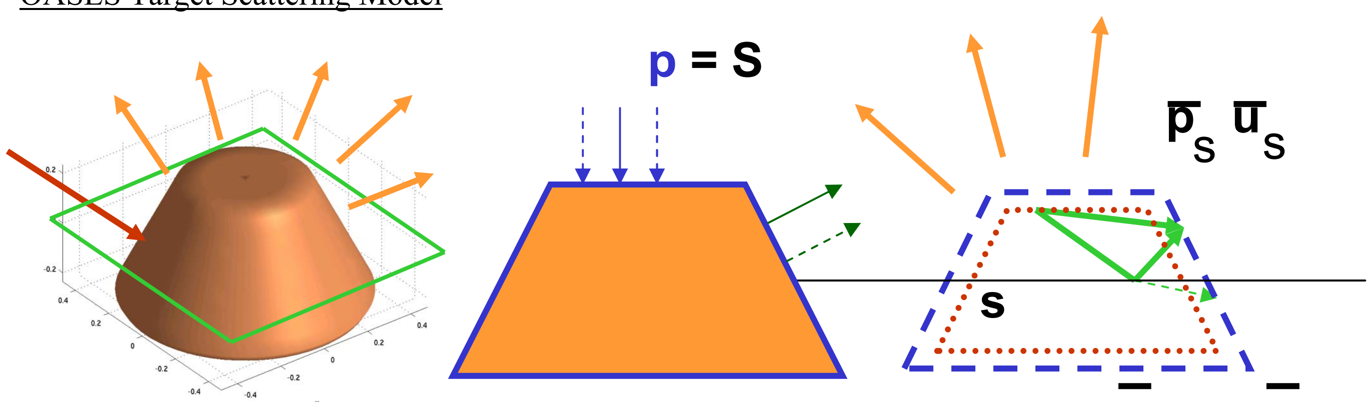

Fig. 1. Virtual source or wavefield superposition approach to scattering from partially or completely buried targets in ocean waveguides.

In support of the analysis of the GOATS'98 and '2000 datasets, the OASES-3D target scattering and propagation model continues to be expanded to allow simulation of bi-static scattering from complex, elastic targets, partially and completely buried. In FY02, a virtual source approach was developed allowing very efficient modeling of the bi-static scattering from completely proud or buried, rigid, void or fluid targets of arbitrary shape. In FY03 this hybrid modeling has been expanded to handle complex target geometry and elasticity, and to allow modeling of scattering from partially buried targets, including multiple scattering between the target and the seabed, providing a new unique modeling capability for target scattering in ocean waveguides. The approach is illustrated schematically in Fig. 1. As the first step OASES is applied to compute the incident acoustic field on the surface of the target, but with the target not present. This incident field is then superimposed with an unknown field produced by distribution of virtual sources 'inside' the target, and including the interface reflected and transmitted components. The strengths the virtual sources can then be found by matching a known 'stiffness' condition $\mathbf{p} = \mathbf{S}\,\mathbf{u}$ for the target. Once the source strengths are determined, these can be fed back into OASES for computing the scattered field. The stiffness matrix, or alternatively the admittance matrix may be computed using any available technique, for example finite elements. An important advantage of this approach is that it does not require the incorporation of the surrounding fluid in the finite element computation, which obviously is a significant simplification.

<u>Analysis of GOATS'98 Bistatic Scattering Data</u>

Continuing analysis of GOATS'98 dataset has been applied toward verification and guidance of the newly developed virtual source and multiple-scattering target scattering models. The analysis was conducted in both spectral and time-frequency domains, thus relating the temporal and spectral features of elastic target signatures to create a complete picture describing the fundamental physical processes contained in this rich and intricate dataset. Furthermore, the systematic analysis of different 3D features of the scattered response has pinpointed the features that currently available models do not properly take into account. Although the absence of these features makes the existing models adequate in monostatic scattering, they are vital in the correct 3D simulation for bistatic configurations. In order to provide a consistent and reliable basis for comparison with the models, the data analysis effort has been concentrated on the analysis of the extensive dataset collected on a fixed 128-element horizontal line array (HLA) suspended over the target area. Auto-regressive (AR) spectral estimation methods have been applied to simulated and experimental time series, illustrating important features of the wave dynamics of resonant elastic wavetypes circumnavigating the shell under varying burial and insonification conditions. Of particular interest for the modeling effort are the phase and group speeds of these waves. In order to identify different waveform signatures in the target response, expected arrival times for each waveform in each considered configuration was calculated based on the sonar and target geometry. Using the travel distances in water and sediment, and their corresponding speeds for azimuthally in plane and out of plane receivers, precise expected times of arrival for each waveform return have been calculated and marked on time-frequency plots.

RESULTS

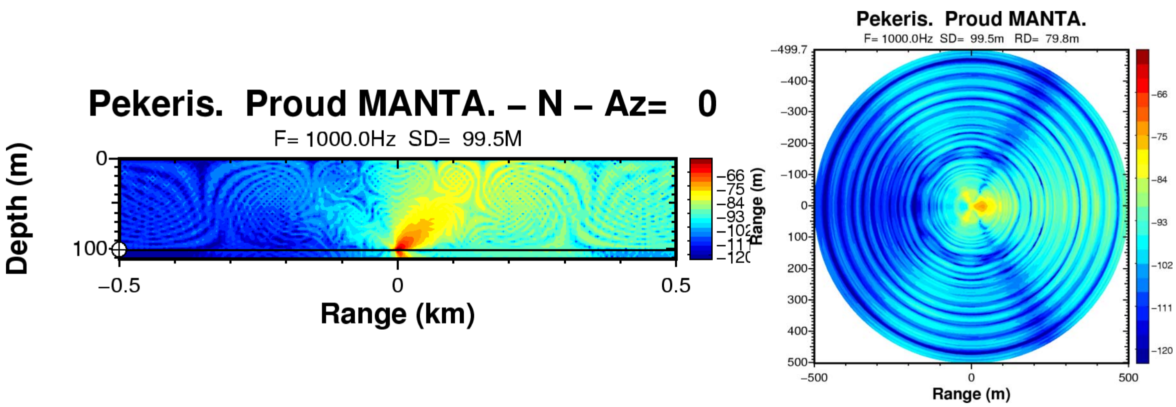

Fig. 2. OASES-FESTA hybrid modeling framework applied to model the scattering of a proud MANTA mine in a shallow water waveguide of 100 m depth. The left plot shows the vertical in-plane scattering, while the right plot shows the horizontal distribution at 75 m depth. A 1 kHz source is at 500 m range to the left.

<u>Modeling of Bistatic Scattering from Proud and Buried Targets</u>

The new hybrid modeling framework described above has been implemented in the OASES modeling infrastructure, with the stiffness matrix computed using a simple FEM model for elastic shells developed at MIT, or the more complex and general FESTA FEM framework developed at SACLANTCEN by Burnett and Zampolli. It is currently being applied in the analysis of the rich GOATS’98 and 2000-02 experimental data. In addition, it is being extensively applied under a new SACLANTCEN JRP on hybrid target modeling for investigating the scattering for complex targets in connection with both MCM and Homeland Security applications. For example, Fig. 2 shows the scattering by a MANTA mine on the seabed 500 m from the source in shallow water of 100 m depth. The left plot shows the vertical, in-plane scattering, and the right plot shows the scattered field in a horizontal plane 20 m above the seabed, both at 1kHz. In both plots the target is at the center, and the source at the left edge. The low backscattering illustrates the stealthiness of the conical shape for mono-static scattering, but obviously, this stealthiness is achieved at the cost of producing a 20 dB bistatic enhancement at approximate 60 degrees bi-static angle. This scenario illustrates how bistatic configurations may significantly improve the detection of monostatically stealthy targets which is the underlying philosophy of the GOATS concept. Note that the MANTA is axisymmetric, so this enhancement could not be achieved by multiple aspect insonification.

<u>Bistatic scattering from buried shells</u>

Unique to bistatic configuration, the effects of counter-clockwise and clockwise elastic waves revolving around the shell in the opposite directions and being launched at different grazing angles are accurately represented in the calculations. Fig. 3 illustrates the two different paths traveled by the clockwise (A_{0I}) and the counter-clockwise (A_{0II}) parts of the flexural Lamb wave being launched at different angles, traveling different path lengths, and arriving to the out of plane receiver at two distinct times.

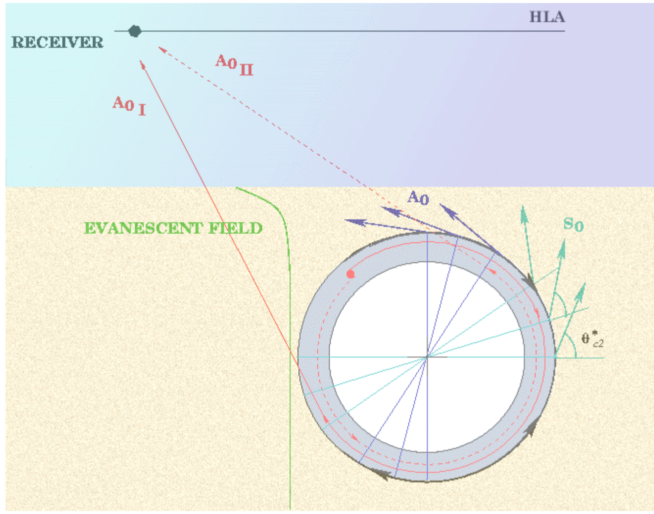

Fig. 3. The clockwise (A_{0I}) and the counter-clockwise (A_{0II}) parts of the Lamb wave circumnavigating the flush buried target.

The time-frequency representation of both model-generated and experimental data was obtained in two ways: 1) by using a non-parametric, FFT-based spectrogram, and 2) by incorporating a parametric AR model to the frequency estimation in the spectrogram. The first method yielded good results in the identification of scattered arrivals, where a reliable agreement between the expected and actual times of arrival was observed. The second method provided superior resolution in both time and frequency domains. Fig. 4 shows the time series and the spectrogram of an azimuthally out-of-plane receiver with respect to the target. The green and black lines represent the calculated times of arrival for S_0 and A_0 waves respectively. The specular reflection is followed by a pair of compressional Lamb waves marked by S_{0I} and S_{0II} and their multiple revolutions S_{0Ix2} and S_{0IIx2}. The pair of flexural Lamb waves A_{0I} and A_{0II}, represented by two black lines, shows that the amplitude and the frequency contents of the two are considerably different.

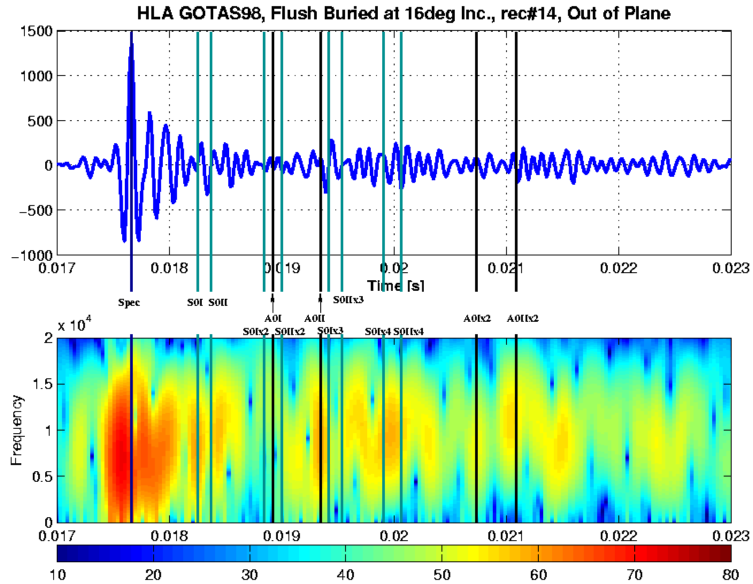

Fig. 4. Time series and spectrogram of GOATS 98 experimental flush buried target data (out-of-plane receiver).

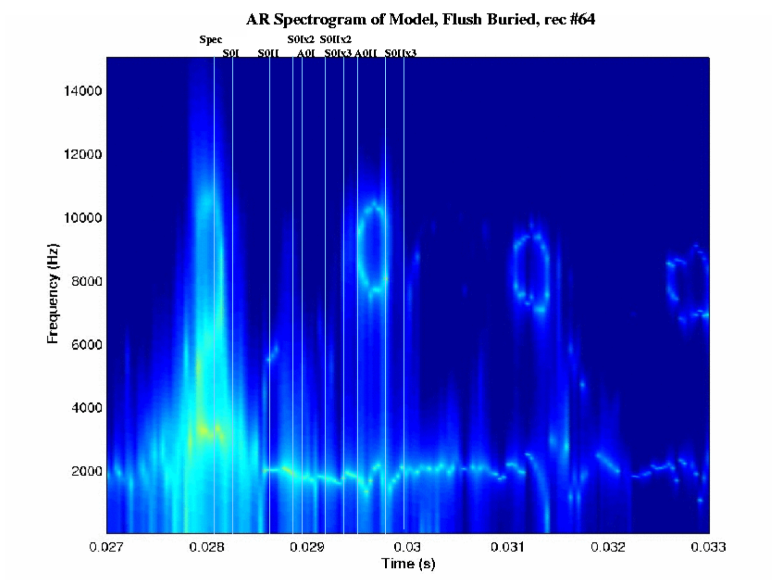

Fig. 5. Auto-regressive (AR) spectrogram of model flush buried target data (in-plane receiver).

Fig. 5 is the AR spectrogram of the OASES 3D model time series when the field scattered by the flush buried target was received by an in-plane receiver. While the high resolution spectrogram clarifies the otherwise blurry frequency content of each arrival, it also pinpoints the reason for the apparent model-experiment time of arrival discrepancy observed earlier in the analysis of this dataset. Namely, the A_{0I} return, which corresponds to the shorter path of the flexural wave, is not represented by the model, leaving a wide gap in time between the target specular reflection and the first flexural return concurrent with the A_{0II} expected arrival.

In order to investigate the vertical angles at which the different waveforms were launched, wideband focused beamforming along the HLA was employed. Fig. 6 shows the beamformed backscattered response of GOATS 98 experimental data received by a sub-array of receiver #1 to receiver #45, where the partially buried target was insonifed using an evanescent incident field. The calculated expected times of arrivals of different waveforms are marked in red and white corresponding to propagating and evanescent incident field initiating two distinct wave groups traveling around the spherical shell.

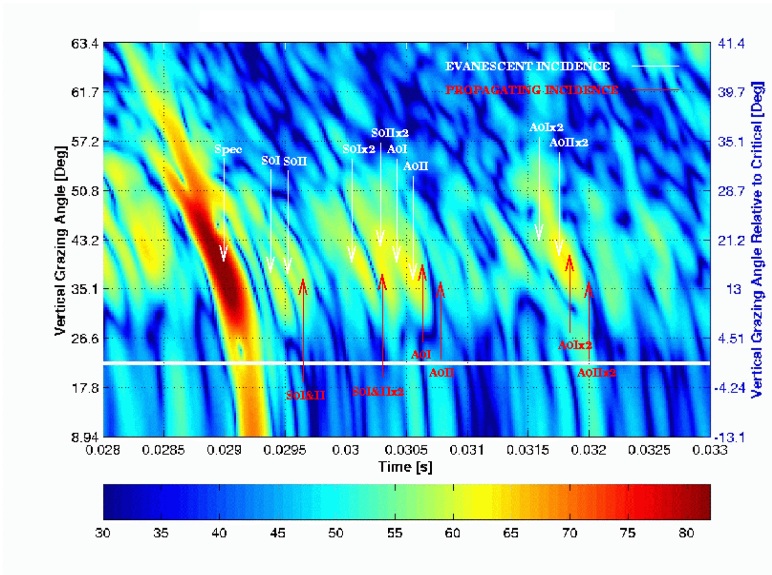

Fig. 6. Focus beamformed response of GOATS 98 partially buried target. Receivers #1-45.

IMPACT/APPLICATION

The long-term impact of this effort is the development of new sonar concepts for VSW MCM, which take optimum advantage of the mobility, autonomy and adaptiveness of the AOSN. For example, bi- and multi-static, low-frequency sonar configurations are being explored for completely or partially proud or buried mines in shallow water, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment.

TRANSITIONS

The GOATS AUV effort has been and is conducted in cooperation with the MIT Sea Grant AUV Laboratory and Bluefin Robotics, a spin-off from the MIT Laboratory. Bluefin is currently developing and building the Odyssey III Battlefield Preparation AUV for ONR, and similar MCM platforms for the Coastal Systems Station (CSS) and QinetiQ (UK), building in part on the experience and results from the GOATS effort.

The results of the multi-vehicle navigation, communication and cooperative behavior is being transitioned into the Autonomous Operations Future Naval Capabilities (AOFNC) project

Demonstratio of Undersea, Autonomous Operation Capabilities and related Technology Development. John Leonard is the MIT PI of this joint project with Bluefin Robotics and the Naval Undersea Warfare Center.

The unique acoustical modeling components are being transitioned to a new SACLANTCEN JRP on hybrid target scatter modeling, initiated with a workshop in July 2003, and involving modeling efforts in UK, France, Germany, Norway, and US, including Coastal System Station, Panama City.

The hybrid modeling framework has been transitioned to the Focused Acoustic Field (FAF) program, carried out jointly by Scripps/MPL and SACLANTCEN, specifically for analysing the feasibillity of using FAF for harbor protection and mine countermeasures purposes.

The results of the GOATS and FAF efforts are currently being transitioned into the new Shallow Water Autonomous Mine Sensing Initiative (SWAMSI) starting FY04, with a joint experiment being planned with SACLANTCEN for July 2004.

The OASES acoustic propagation framework continues to be maintained and expanded. It is continuously being exported or downloaded from the OASES web site (http://acoustics.mit.edu/arctic0/henrik/www/oases.html), and used extensively by the community as a reference model for ocean seismo acoustics in general.
Parts of OASES modeling framework has been incorporated in the certified Ocean Acoustic Modeling Library (OAML). Thus the GABIM generic bottom interaction model uses OASES as its core computational engine, while the OASR bottom loss model is in the process of being certified. OASES is also the computational engine use by the SEALAB sonar simulator being developed and used by a parnership between VASA Associates and Lockheed-Martin, Eagan in for the underwater acoustic system design associated with the NAVAIR Multi-Mission Aircraft (MMA) program.

RELATED PROJECTS

This effort is part of the US component of the GOATS`2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre. The MIT GOATS effort is funded jointly by ONR codes 321OA (Simmen), 321OE (Swean), 321TS (Johnson), and 322OM (Curtin).

The GOATS effort is strongly related to the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00. Thus the GOATS'98 experimental effort was funded in part by the AOSN MURI, (PI: J. Bellingham). In terms of the fundamental seabed penetration physics there are strong relations to the High-Frequency Bottom Penetration DRI (PI: E. Thorsos). This effort also builds on acoustic modeling efforts initiated under the Sea-Ice Mechanics Initiative (SIMI), and continued under funding from ONR code 321OA (Simmen).

With its heavy focus on Synthetic Aperture Processing approaches and their extension to bi- and multistatic configurations in multipath SW VSW environments, there are strong relations to the ONR SASSAFRASS project (code 321TS and 321OA).

The OASES modeling framework being maintained and upgraded under this contract is being used intensively as part of the MIT AREA (Adaptive Rapid Environmental Assesment) component of the new ONR "Capturing Uncertainty" DRI (Grant # N0014-01-1-0817), aimed at mitigating the effect of

sonar performance uncertainty associated with environmental uncertainty by adaptively deploying environmental assesment resources.

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